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VOCs (Volatile Organic Chemicals) in Drinking Water: Cost of Removal

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16. ABSTRACT

There is growing concern over the quality of the nations groundwater resources. Instances of ground water contamination from organic chemicals have been reported in virtually all states. Long-term policy should be directed toward the protection of ground-water quality. Although, ideally, ground water contamination should be prevented, existing contamination problems must be addressed. This paper discusses several control technology options available to treat ground water for organic chemical contamination. A cost and performance analysis is presented in order to guide the selection of control technologies for seven major contaminant: trichloroethylene; tetrachloroethylene; 1,1,1-trichloroethane; carbon tetrachloride; cis-,2-dichloroethylene; 1,2-dichloroethane; 1,1-dichloroethylene. In all cases aeration is the cheapest alternative for treatment. If adsorption is required, home units using granular activated carbon (GAC) may prove to be cheaper than central adsorption treatment.

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VOCs in Drinking Water: Cost of Removal

By Robert M. Clark,[1] M. ASCE, Richard G. Eilers,[2] and James A. Goodrich[3]

Abstract: There is growing concern over the quality of the nations ground-water resources. Instances of ground water contamination from organic chemicals have been reported in virtually all states. Long-term policy should be directed toward the protection of ground-water quality. Although, ideally, ground water contamination should be prevented, existing contamination problems must be addressed. This paper discusses several control technology options available to treat ground water for organic chemical contamination. A cost and performance analysis is presented in order to guide the selection of control technologies for seven major contaminants: trichloroethylene; tetrachloroethylene; 1,1,1-trichloroethane; carbon tetrachloride; cis-1-2-dichloroethylene; 1-2 dichloroethane; 1-1 dichloroethylene. In all cases aeration is the cheapest alternative for treatment. If adsorption is required, home units using granular activated carbon (GAC) may prove to be cheaper than central adsorption treatment.

Introduction

Historically, ground water has been viewed as a relatively pristine source and is generally used for drinking water without major treatment other than disinfection. However, recent data from EPA and state monitoring surveys indicate that a significant number of drinking water supplies derived from ground waters, as well as surface waters, contain some volatile organic chemicals. Volatile compounds are generally defined in terms of their Henry's Constant. As a rough approximation, any compound with a Henry's Constant of 0.1×10^{-3} atm-m^3/mole or greater may be considered volatile. While surface waters subject to industrial contamination can contain a broad spectrum of synthetic organic chemicals, typically their concentrations are in the low microgram-per-liter range (e.g., less than 5 ug/L). Although only a small percentage of ground-water supplies have been found to be contaminated, this contamination is usually by one, two or several discrete compounds, at concentrations much higher (e.g., 100 to 1,000 ug/L) than normally found in surface waters.

Contamination by organic chemicals is generally associated with situations in which they are made, spilled, used or discarded (5,8,9). Once

[1]Chf., Physical and Chemical Contaminant Removal Branch, Drinking Water Research Div., Municipal Environmental Research Lab., U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

[2]Operations Research Analyst, Systems and Cost Evaluation Section, Physical and Chemical Contaminant Removal Branch, Drinking Water Research Division, Municipal Environmental Research Lab., U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

[3]Environmental Scientist, Systems and Cost Evaluation Section, Physical and Chemical Contaminant Removal Branch, Drinking Water Research Division, Municipal Environmental Research Lab., U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

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a community water supply is identified as being contaminated, the options available range from treating the existing supply to development of a new source.

EPA is investigating the performance and costs of treatment technology to apply when it may be impossible to develop a new, uncontaminated source of supply. The most commonly identified methods for removal of these volatile organic chemicals are various forms of aeration and granular activated carbon adsorption. In a given case other methods may be appropriate, but for the purposes of this paper the analysis will be confined to diffused and tower aeration and fixed-bed granular activated carbon adsorption.

This paper will discuss and evaluate preliminary cost estimates for hypothetical ground-water contamination situations involving the six most commonly found volatile organic chemicals: trichloroethylene; tetrachloroethylene; 1,1,1-trichloroethane; cis-1,2-dichloroethylene; 1,2-dichloroethane; and 1,1-dichloroethylene. An examination will be made of the proper scale of application of aeration and adsorbtion technology and of other options for minimizing costs, such as regionalization or the installation of home treatment units.

Performance Characteristics

In this section, the performance characteristics of the three types of technology used to remove volatile organics from ground water will be considered—granular activated carbon adsorption, tower aeration and diffused air aeration (3,4).

Granular activated carbon (GAC) is an adsorbent technique very effective for removing a broad spectrum of organics from drinking water. Table 1 summarizes the performance of GAC in pounds of carbon/thousand gallons (10 m^3 water/m^3 carbon) of water required to remove the selected volatile organics from a given influent concentration to a target effluent concentration (3,4). For example, given an influent concentration of trichloroethylene of 1,000 μg/L to be reduced to 0.1 μg/L, the required carbon usage is 0.50 lb of carbon 1,000 gal of water (6.9×10^3 m^3 water/m^3 carbon). Carbon usage is based on a given application rate and contact time.

Table 2 summarizes the air-to-water ratios required for using air stripping to remove volatile organic chemicals from water (3,4). The influent concentration in micrograms per liter is given versus the effluent concentration to be achieved, and the elements of the Table contain the required air-to-water ratio necessary to achieve a given level of removal. For example, if we wish to reduce an influent concentration of trichloroethylene from 1,000 μg/L to 0.1 μg/L, the required air-to-water ratio is 76:1. These air-to-water ratios are for both diffused air aeration and tower stripping.

Table 3 contains selected physical properties for the volatile organic chemicals (VOCs) examined (4). For each chemical, the molecular weight, density, Henry's Constant and solubility vapor pressure and saturation condition are given. These physical and chemical characteristics play a role in the removal efficiencies associated with each contaminant, as will be discussed later.

TABLE 1.—Estimated Carbon Usage Necessary to Achieve Desired Effluent Concentration[a]

Volatile organic contaminants (1)	Influent concentration, in micrograms per liter (2)	Carbon Usage, in Pounds of Carbon per Thousand Gallons of Water (10^3 m^3 Water/m^3 Carbon), Required for Desired Levels of Effluent Concentration[b]				
		0.1 micrograms per liter (3)	1 micrograms per liter (4)	10 micrograms per liter (5)	50 micrograms per liter (6)	100 micrograms per liter (7)
Trichloroethylene	1,000	0.50 (6.9)	0.4 (8.7)	0.32 (10.4)	0.29 (11.6)	0.28 (12.1)
	100	0.20 (16.7)	0.15 (22.1)	0.12 (27.7)	0.11 (31.5)	— —
	10	0.08 (41.0)	0.06 (60.3)	— —	— —	— —
	1	0.03 (96.1)	— —	— —	— —	— —
1,1,1-Trichloroethane	1,000	2.0 (1.7)	1.3 (2.7)	1.0 (3.3)	0.86 (3.9)	0.80 (4.2)
	100	0.4 (8.1)	0.26 (13.0)	0.19 (18.0)	0.16 (21.0)	— —
	10	0.09 (37.0)	0.05 (70.0)	— —	— —	— —
	1	0.02 (169)	— —	— —	— —	— —
Tetrachloroethylene	1,000	0.23 (14.7)	0.16 (20.7)	0.13 (26.7)	0.11 (30.9)	0.10 (32.7)
	100	0.08 (40.1)	0.06 (59.6)	0.41 (81.2)	0.03 (100)	— —
	10	0.03 (111)	0.02 (200)	— —	— —	— —
	1	0.01 (306)	— —	— —	— —	— —
Carbon tetrachloride	1,000	0.7 (4.8)	0.51 (6.5)	0.41 (8.2)	0.35 (9.5)	0.34 (9.9)
	100	0.48 (7.0)	0.32 (10.6)	0.24 (14.0)	0.21 (16.3)	— —
	10	0.32 (10.4)	0.19 (18.0)	— —	— —	— —
	1	0.22 (15.5)	— —	— —	— —	— —
Cis-1,2-Dichloroethylene	1,000	3.0 (1.1)	0.26 (1.3)	2.2 (1.5)	2.0 (1.7)	1.8 (1.9)
	100	1.0 (3.3)	0.8 (4.2)	0.65 (5.2)	0.55 (5.9)	0.55 —
	10	0.3 (10.1)	0.2 (14.6)	— —	— —	— —
	1	0.1 (31.1)	— —	— —	— —	— —
1,2-Dichloroethane	1,000	1.7 (2.0)	1.1 (3.1)	0.82 (4.1)	0.68 (4.9)	0.65 (5.2)
	100	1.0 (3.5)	0.62 (5.4)	0.46 (7.3)	0.39 (8.6)	— —
	10	0.65 (5.2)	0.36 (9.3)	— —	— —	— —
	1	0.45 (7.6)	— —	— —	— —	— —
1,1-Dichloroethylene	1,000	0.61 (5.5)	0.45 (7.4)	0.36 (9.6)	0.31 (11.0)	0.29 (11.3)
	100	0.21 (15.9)	0.14 (23.0)	0.11 (30.8)	0.09 (35.9)	— —
	10	0.07 (45)	0.04 (77.4)	— —	— —	— —
	1	0.03 (132)	— —	— —	— —	— —

[a]See Ref. 3.
[b]Mean loading, GAC usage.

Tables 1 and 2 provide useful point estimates of removal efficiencies for carbon and aeration. However there is no systematic means of estimating removal efficiencies at intermediate points. Therefore, regression models, described in the following sections, were developed to provide this flexibility.

Carbon Adsorption.—A regression model was developed to relate the performance of GAC adsorption to various parameters. Eq. 1 shows the relationship between carbon use rate (UR) in pounds of carbon per thousand gallons of water passing the carbon filter, in order to reach a given effluent target. The relationship is as follows:

$$UR = 100.1\ RM^{4.52}\ IF^{0.31}\ ML^{-1.94}\ SL^{0.31} \quad (R^2 = 0.81) \ldots\ldots\ldots\ldots\ldots\ (1)$$

in which UR = pounds of carbon per thousand gallons of water passing the carbon filter; RM = removal as a decimal; IF = influent concentration

TABLE 2.—Estimated Air-to-Water Ratios Necessary to Achieve Desired Effluent Concentration[a]

Volatile organic contaminants (1)	Influent concentration, in micrograms per liter (2)	Air-to-Water Ratios Required to Achieve Desired Levels of Effluent Concentration[a]				
		0.1 micrograms per liter (3)	1 micrograms per liter (4)	10 micrograms per liter (5)	50 micrograms per liter (6)	100 micrograms per liter (7)
Trichloroethylene	1,000	76:1	54:1	32:1	17:1	11:1
	100	54:1	32:1	11:1	1:1	—
	10	32:1	11:1	—	—	—
	1	11:1	—	—	—	—
Tetrachloroethylene	1,000	96:1	72:1	45:1	26:1	18:1
	100	72:1	45:1	18:1	1:1	—
	10	45:1	18:1	—	—	—
	1	18:1	—	—	—	—
1,1,1-Trichloroethane	1,000	198:1	90:1	35:1	14:1	8:1
	100	90:1	35:1	8:1	1:1	—
	10	35:1	8:1	—	—	—
	0	8:1	—	—	—	—
Carbon tetrachloride	1,000	19:1	15:1	10:1	6:1	4:1
	100	15:1	10:1	6:1	1:1	—
	10	10:1	6:1	—	—	—
	1	6:1	—	—	—	—
Cis-1,2-Dichloroethylene	1,000	104:1	77:1	52:1	34:1	26:1
	100	77:1	52:1	26:1	4:1	—
	10	52:1	26:1	—	—	—
	1	26:1	—	—	—	—
1,2-Dichloroethane	1,000	56:1	42:1	28:1	18:1	14:1
	100	42:1	28:1	14:1	—	—
	10	28:1	14:1	—	—	—
	1	14:1	—	—	—	—
1,1-Dichloroethylene	1,000	10:1	8:1	5:1	3:1	3:1
	100	8:1	5:1	—	—	—
	10	5:1	3:1	—	—	—
	1	3:1	—	—	—	—

[a]See Ref. 3.

in micrograms per liter; ML = molecular weight of compound in grams per mole; and SL = solubility of compound in milligrams per liter.

Carbon use rate is a particularly good measure of performance because it incorporates contact time and loading rate on the filter. To illustrate the use of Eq. 1, assume that trichloroethylene is to be removed from an influent level of 1,000 μg/L to 100 μg/L (RM = 0.90). From Table 3 we know that ML = 132 g/mole and SL = 1,000 mg/L.

Substituting the appropriate values in Eq. 1 yields

$$UR = 100.1\ (0.90)^{4.52}\ (1{,}000)^{0.31}\ (132)^{-1.94}\ (1{,}000)^{0.31}$$

$$UR = 0.34 \text{ lb of carbon/1,000 gal of water} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

As can be seen from Eq. 1, the "R^2" values are relatively high, and therefore duplicate the values in Table 1 within reasonable limits. The

TABLE 3.—Physical Properties of Volatile Organic Chemicals[a]

Chemical (1)	Molecular weight, in grams per mole (2)	Density, in grams per milliliter (3)	Henry's Constant (atm-m^3/10^{-3} mole) (4)	Solubility, in milligrams per liter (5)	Vapor pressure, in millimeters Hg (6)	Saturated condition[b] (7)
Trichloroethylene	132	1.46	0.485	1,000	74	UN
1,1,1-Trichloroethane	133	1.34	0.61	5,000	100	SAT
Tetrachlorethylene	166	1.62	1.15	145	18.6	UN
Carbon tetrachloride	154	1.59	1.2	800	91.3	SAT
Cis-1,2-dichloroethylene	97	1.29	0.31	3,500	206	UN
1,2-Dichloroethane	99	1.24	0.05	8,700	82	SAT
1,1-Dichloroethylene	97	1.22	7.8	40	495	UN

[a]See Ref. 4.
[b]UN = unsaturated; SAT = saturated.

data in Table 1 are in turn derived from a series of bench, pilot and field scale experiments as discussed in Love et al. (3).

Air Stripping.—A similar approach was used to obtain a performance-based equation for air stripping using the data in Table 2. The response variable chosen was air-to-water ratio. The resulting relationship is given as

$$AW = 74.6\, RM^{12.44}\, SL^{0.37}\, V^{-0.45}\, ML^{-0.18}\, (0.33)^{S} \quad (R^2 = 0.86) \ldots\ldots\ldots (3)$$

in which AW = air-to-water ratio; RM = removal as a decimal; V = vapor pressure; SL = solubility; ML = molecular weight; and S = saturation state: $S = 1$ for saturated compounds, $S = 0$ for unsaturated compounds.

Compounds in which all carbon-to-carbon bonding in the molecule are single bonds, as in the methane series of hydrocarbons, are called saturated compounds. Compounds in which carbon-to-carbon bonding anywhere within the molecule is represented by double or triple bonds, as in the ethylene and acetylene series of hydrocarbons, are called unsaturated compounds.

Eq. 3 duplicates the experimental data in Table 3, which is from Love et al. (3).

For trichloroethylene, substituting the appropriate values in Eq. 3 (assuming 90% removal) yields

$$AW = 74.6\, (0.90)^{12.44}\, (1{,}000)^{0.37}\, (74)^{-0.45}\, (132)^{-0.18}\, (0.33)^{0}$$

$$AW = 15.5 \ldots\ldots\ldots (4)$$

Cost Assumptions

In this section treatment costs are developed to compliment the performance data discussed in the previous section. A treatment configuration is assumed and costs are estimated to achieve a given level of removal for the VOCs considered.

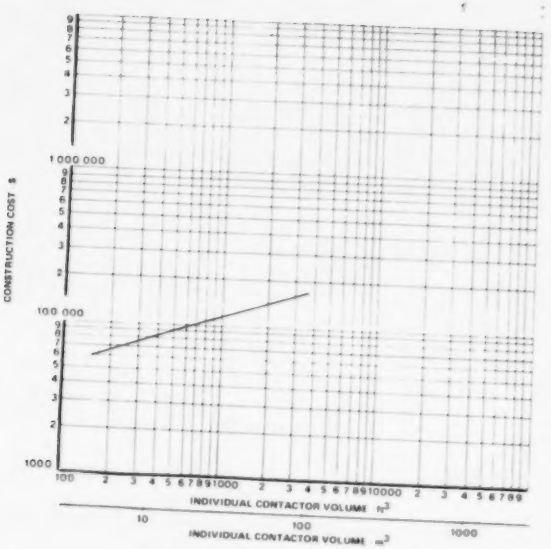

FIG. 1.—Construction Cost Data

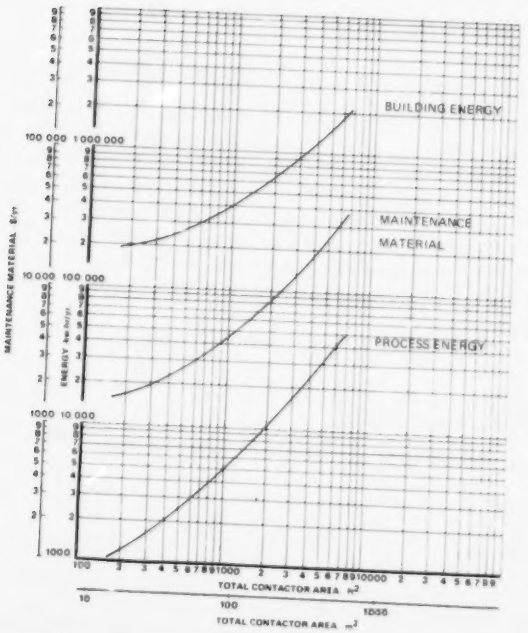

FIG. 2.—Operation and Maintenance Cost Data

Typical of the basic data used in generating these data are the cost curves for carbon contactors shown in Figs. 1 and 2. Fig. 1 shows the construction cost in dollars versus a design parameter which is cubic feet of volume. Fig. 2 shows contactor surface area versus operation and maintenance costs for construction, energy, labor and maintenance material costs, and can be updated for current costs. These data are from Clark and Dorsey (1).

The treatment cost estimates were based on the configuration shown in Fig. 3. In this case, a ground-water source is assumed together with one of three technologies—aeration towers, diffused-air aeration or granular carbon adsorption. The effluent stream from the treatment process is chlorinated, goes to a clear well, and then is distributed to the system. For this analysis it is assumed that the technology is used in a small system. A pumping head of 40 ft is assumed to include process pumping and low head distribution. In this paper, we will examine the cost trade-offs among the three technologies, assuming flows of 0.5 (1,896 m^3/day), 1 (3,785 m^3/day) and 10 mgd (3,785 m^3/day), all operating at 70% capacity (1).

The following assumptions are used for the aeration towers. The towers are assumed to be rectangular, with a height of 10 ft (3 m), with an air supply of 52 standard cu ft/min/sq ft (137 standard L/min/m^2) of surface area. They are assumed to have electrically driven induced draft fans, stacks and draft eliminators. The tower costs do not include supply pumps or underflow pumps.

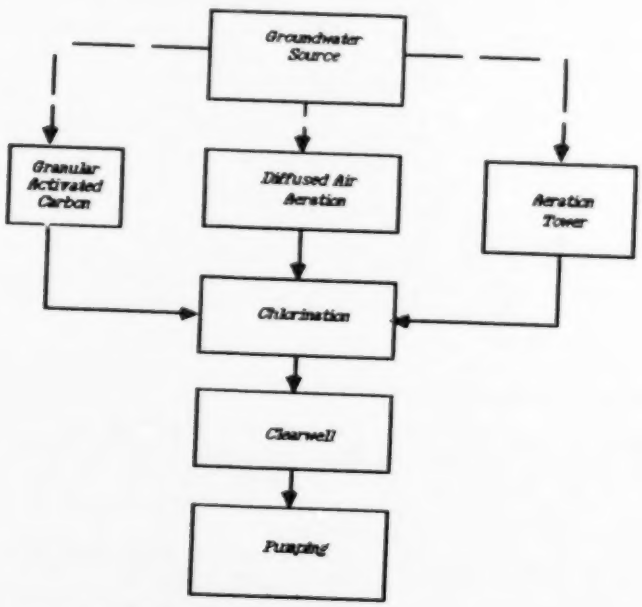

FIG. 3.—Assumed Flow Configuration for Analysis

TABLE 4.—Design Assumptions for Plant Configurations

Plant configurations (1)	Clearwell storage—ground level, in gallons (cubic meters) (2)	Chlorination feed and storage, in pounds per day (kilograms/day) (3)	Pumping head, in feet (meters) (4)
500,000 gallons per day (1,893 cubic meters per day)	50,000 (189)	58 (26)	40 (12)
1,000,000 gallons per day (3,785 cubic meters per day)	100,00 (379)	117 (53)	40 (12)
10,000,000 gallons per day (37,853 cubic meters per day)	1,000,000 (3,785)	1,170 (531)	40 (12)

Aeration basins are assumed to be rectangular, with a depth of 12 ft (3.5 m), with a diffused air supply of 5 standard cu ft/min/sq ft (14 standard L/min/m^2) of basin floor area.

Assumptions for adsorption were as follows: Three gravity downflow steel contactors operated in series, with an initial carbon supply and carbon usage based on six-month disposal at a cost of 70¢/lb ($1.54/kg).

The assumptions for chlorination included a feed system with no basin and a building for cylinder storage. The assumed dose is 2 mg/L, and the cost of chlorine is assumed at $320/ton (35¢/kg).

Clearwell storage was assumed to be above ground with a capacity equal to 10% of daily flow. The unit process pumps and low head distribution pumps were assumed to generate a head of 40 ft (12 m).

Also not included were expenditures for land, corrosion control, fences, off-gas handling or carbon disposal. Table 4 contains specific assumptions for the 0.5 (1,893 m^3/day), 1 (3,785 m^3/day) and 10 mgd (37,853 m^3/day) plant configurations. The following assumptions were made: labor costs at $9/hr; electricity costs at 5¢/kilowatt-hour; amortization interest rate at 10%; amortization period of 20 yr; ENR Construction Cost Index (1982) of 361.

Cost and Performance Calculations

Using the cost data, design assumptions and performance data listed in the previous section, cost comparisons were made among the three technologies to remove trichloroethylene; tetrachloroethylene; 1,1,1-trichloroethane; carbon tetrachloride; cis-1,2-dichloroethylene; 1,2-dichloroethane; and 1,1-dichloroethylene.

Figs. 4, 5 and 6 show the costs for removing trichloroethylene at the 0.5 (1,893 m^3/day), 1 (3,785 m^3/day) and 10 mgd (37,835 m^3/day) design levels. Calculations are made for removal efficiencies between 90 and 99.99%. As might be expected, the unit costs for all three technologies

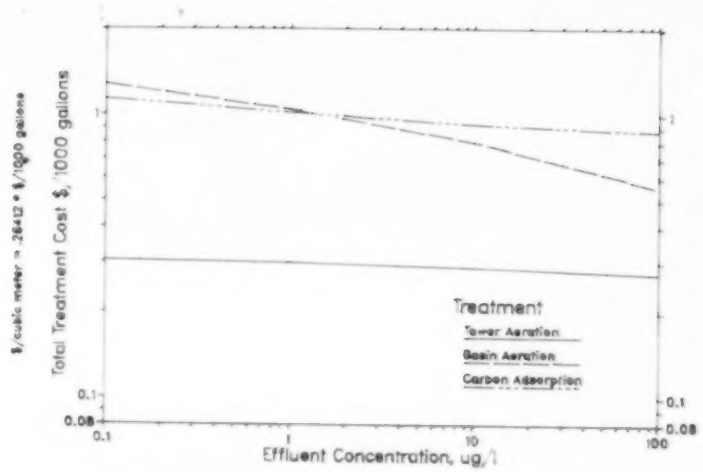

FIG. 4.—Treatment (Trichloroethylene 0.5 mgd; Influent Concentration = 1,000 μg/L; Sept. '82 Dollars)

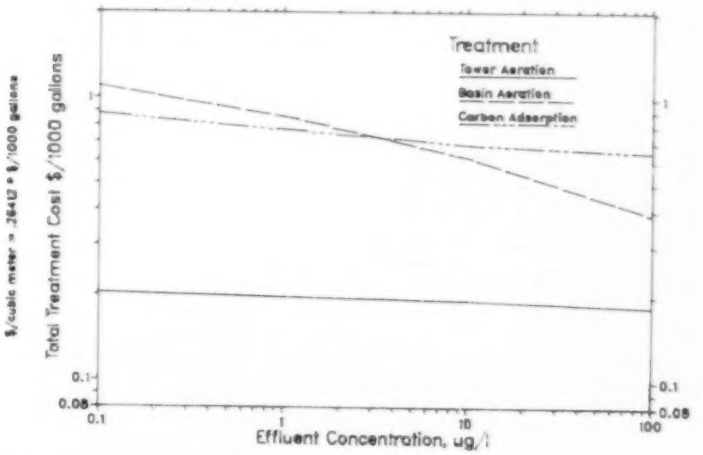

FIG. 5.—Treatment (Trichloroethylene 1.0 mgd; Influent Concentration = 1,000 μg/L; Sept. '82 Dollars)

drop with increasing design capacity. Carbon adsorption becomes somewhat less expensive than basin aeration with increasing design capacity. At all design levels and for all removals, assuming an initial concentration of 1,000 μg/L, tower aeration is the cheapest technology.

Fig. 7 shows the cost for removing tetrachloroethylene at the 0.5 mgd (1,893 m^3/day) capacity level. As can be seen, the cost of tower aeration for removing tetrachloroethylene is slightly higher than for removing

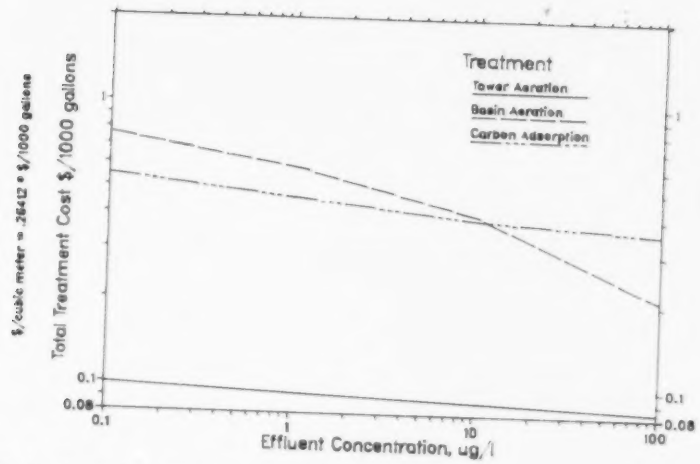

FIG. 6.—Treatment (Trichloroethylene 10 mgd; Influent Concentration = 1,000 µg/L; Sept. '82 Dollars)

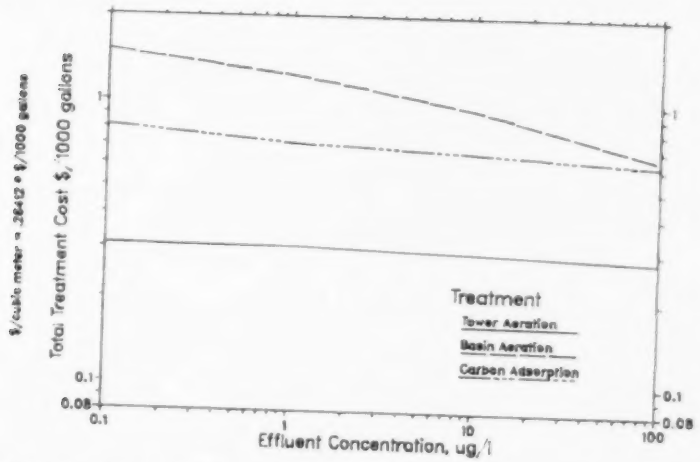

FIG. 7.—Treatment (Tetrachloroethylene 0.5 mgd; Influent Concentration = 1,000 µg/L; Sept. '82 Dollars)

trichloroethylene at the 0.5 mgd capacity level. Tetrachloroethylene is more difficult to remove from solution, as evidenced by the higher air-to-water ratios required to achieve given the effluent targets shown in Table 2. However, the cost for carbon adsorption is lower for tetrachloroethylene than for trichloroethylene. Obviously, tetrachloroethylene is more adsorbable than trichloroethylene. The somewhat higher molecular weight for tetrachloroethylene would tend to confirm this re-

TABLE 5.—Cost Data Summary (VOC Removal Costs)

Contaminant (1)	Capacity[a]		Percent removal (4)	Cost, in Dollars per Thousand Gallons[b]		
	Millions of gallons per day (2)	Micrograms per liter (3)		Tower (5)	Aeration basin (6)	Carbon adsorption (7)
Trichloroethylene	0.5	100	90	0.273	0.546	0.868
		10	99	0.287	0.793	0.918
		1	99.9	0.296	1.032	1.010
		0.1	99.99	0.303	1.270	1.124
	1	100	90	0.182	0.383	0.637
		10	99	0.191	0.611	0.679
		1	99.9	0.196	0.850	0.765
		0.1	99.99	0.202	1.088	0.867
	10	100	90	0.083	0.207	0.356
		10	99	0.088	0.403	0.390
		1	99.9	0.093	0.587	0.458
		0.1	99.99	0.099	0.755	0.543
Tetrachloroethylene	0.5	100	90	0.279	0.637	0.610
		10	99	0.293	0.935	0.660
		1	99.9	0.302	1.228	0.705
		0.1	99.99	0.308	1.486	0.805
	1	100	90	0.186	0.460	0.453
		10	99	0.194	1.752	0.502
		1	99.9	0.201	1.046	0.548
		0.1	99.99	0.206	1.296	0.651
	10	100	90	0.085	0.277	0.197
		10	99	0.091	0.514	0.224
		1	99.9	0.098	0.726	0.251
		0.1	99.99	0.103	0.905	0.313
1,1,1-Trichloroethane	0.5	100	90	0.270	0.502	1.445
		10	99	0.289	0.825	1.651
		1	99.9	0.307	1.421	1.945
		0.1	99.99	0.332	2.572	2.605
	1	100	90	0.180	0.348	1.396
		10	99	0.192	0.644	1.500
		1	99.9	0.205	1.234	1.801
		0.1	99.99	0.230	2.313	2.402
	10	100	90	0.082	0.176	0.802
		10	99	0.089	0.430	0.973
		1	99.9	0.102	0.860	1.229
		0.1	99.99	0.122	1.821	1.818
Carbon tetrachloride	0.5	100	90	0.264	0.428	0.942
		10	99	0.287	0.531	1.021
		1	99.9	0.272	0.600	1.132
		0.1	99.99	0.280	0.648	1.340
	1	100	90	0.176	0.292	0.703
		10	99	0.181	0.371	0.775
		1	99.9	0.184	0.427	0.940
		0.1	99.99	0.186	0.470	1.063
	10	100	90	0.081	0.133	0.408

TABLE 5.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		10	99	0.083	0.196	0.467
		1	99.9	0.084	0.247	0.550
		0.1	99.99	0.085	0.286	0.719
Cis-1,2-Dichloro-ethylene	0.5	100	90	0.284	0.727	2.513
		10	99	0.296	1.010	2.791
		1	99.9	0.304	1.281	3.153
		0.1	99.99	0.310	1.572	3.511
	1	100	90	0.189	0.547	2.156
		10	99	0.196	0.828	2.417
		1	99.9	0.202	1.098	2.760
		0.1	99.99	0.208	1.379	3.099
	10	100	90	0.087	0.350	1.735
		10	99	0.093	0.571	1.989
		1	99.9	0.099	0.763	2.327
		0.1	99.99	0.104	0.966	2.660
1,2-Di-chloro-ethane	0.5	100	90	0.276	0.587	1.286
		10	99	0.285	0.749	1.465
		1	99.9	0.292	0.901	1.748
		0.1	99.99	0.297	1.054	2.322
	1	100	90	0.184	0.415	1.015
		10	99	0.190	0.568	1.177
		1	99.9	0.194	0.720	1.437
		0.1	99.99	0.197	0.871	2.980
	10	100	90	0.084	0.237	0.675
		10	99	0.087	0.368	0.820
		1	99.9	0.090	0.489	1.057
		0.1	99.99	0.094	0.603	1.566
1,1-Di-chloro-ethylene	0.5	100	90	0.262	0.406	0.880
		10	99	0.265	0.448	0.963
		1	99.9	0.270	0.500	1.066
		0.1	99.99	0.272	0.531	1.243
	1	100	90	0.174	0.274	0.647
		10	99	0.177	0.307	0.721
		1	99.9	0.180	0.348	0.814
		0.1	99.99	0.181	0.371	0.977
	10	100	90	0.080	0.121	0.364
		10	99	0.081	0.144	0.423
		1	99.9	0.082	0.176	0.499
		0.1	99.99	0.083	0.196	0.640

[a]To convert from mgd to m^3/day, multiply by 3,785.
[b]To convert from dollars/1,000 gal to dollars/m^3 multiply by 0.26412.

sult. Table 5 summarizes the unit removal costs for the contaminants considered. Two obvious factors that influence the unit costs are system size and percent removal. Table 6 shows the unit costs associated with chlorination, the clearwell and pumping unit operations. As can be seen for a given system, these unit costs are constant but vary with system size. By subtracting these unit costs, one can calculate the unit costs directly for a given technology. In order to study these factors more

TABLE 6.—Unit Costs for Chlorination, Clearwell and Pumping

System size, in million gallons per day (1)	Unit process (2)	Capital cost, in dollars per thousand gallons (3)	O&M cost, in dollars per thousand gallons (4)
0.5	Chlorination	0.035	0.043
0.5	Clearwell	0.065	0.000
0.5	Pumping	0.041	0.055
1.0	Chlorination	0.024	0.037
1.0	Clearwell	0.041	0.000
1.0	Pumping	0.024	0.033
10.0	Chlorination	0.012	0.031
10.0	Clearwell	0.016	0.000
10.0	Pumping	0.007	0.002

completely, a sensitivity analysis designed to examine the impact of these variables was performed in the following section.

Sensitivity Analysis

In order to study the relative impact of air-to-water ratio and use rate requirements versus system size on cost, simple regression models were developed. These equations are discussed in the following sections.

Adsorption Cost Equation.—The carbon adsorption cost equation was developed as

$$C_A = K_A Q^a UR^b \quad (R^2 = 0.96) \quad \ldots\ldots (5)$$

in which C_A = unit cost for carbon adsorption in dollars per 1,000 gallons; $K_A = 3.11$; $a = -0.22$; $b = 0.68$; UR = carbon use rate in pounds of carbon per 1,000 gallons; and Q = system design capacity in million gallons per day at 70% capacity.

Tower Cost Equation.—The basic engineering design parameters that have primary impact on the cost of stripping VOCs are system size and air-to-water ratio. Therefore, an equation was developed for packed-tower aeration:

$$C_T = K_T Q^c AW^d \quad (R^2 = 0.98) \quad \ldots\ldots (6)$$

in which C_T = unit cost for packed tower aeration in dollars per 1,000 gallons; $K_T = 0.17$; $c = -0.37$; $d = 0.06$; Q = system design capacity in million gallons per day at 70% capacity; and AW = air-to-water ratio (volume-to-volume) required to remove a contaminant to a given level.

Diffused Air Cost Equation.—A similar equation for diffused air aeration was derived as follows:

$$C_B = K_B Q^e AW^f \quad (R^2 = 0.92) \quad \ldots\ldots (7)$$

in which C_B = unit cost for diffused air aeration, in dollars per 1,000 gallons; $K_B = 0.12$; $e = -0.23$; and $f = 0.52$.

Comparisons.—From the three equations it is clear that basin aeration and carbon adsorption are less sensitive to system size (Q) than is tower aeration.

By comparing Eqs. 6 and 7, it is also clear that diffused air aeration is much more sensitive to air-to-water ratio requirements than is packed tower aeration. Packed tower aeration, therefore, is a technology that could be used in situations where the influent concentrations might be highly variable.

Two cost minimization options for removing volatiles are discussed in the following section.

Cost Minimization Options

In this section two options will be considered as alternatives to minimize the cost of VOC removal. The first is regionalization, which assumes that the cost of carbon can be minimized by sharing the costs of reactivation among several utilities. The two sloping lines in Fig. 8 represent the cost of carbon with and without reactivation for trichloroethylene at the 99% removal level. The regional reactivation option would lie somewhere in the envelope between carbon with and without on-site reactivation. The three horizontal lines represent home treatment units with three different GAC cartridge replacement cycles. In this case, separate in-house units are assumed based on the costs in Table 7 (7).

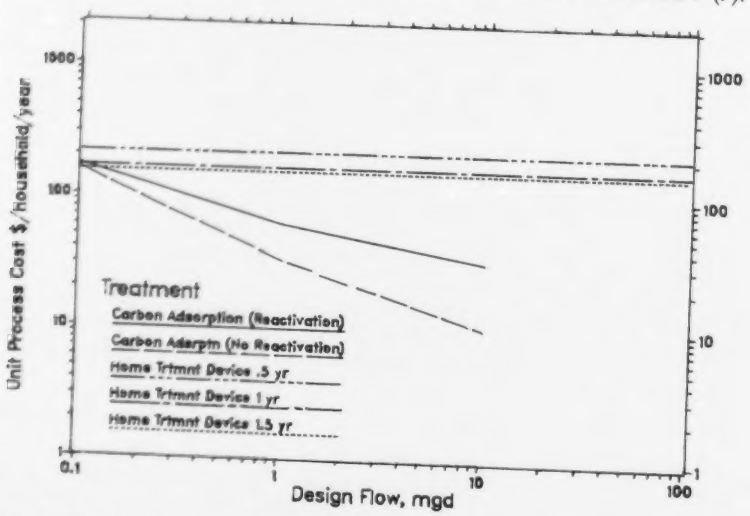

FIG. 8.—Treatment (Trichloroethylene 99% Removal; Influent Concentration = 1,000 μg/L; Sept. '82 Dollars)

TABLE 7.—Cost Assumptions for Home Unit Adsorption

Item (1)	Cost, in dollars (2)
Initial unit cost	50
Quarterly sample	15
Replacement cartridge	50

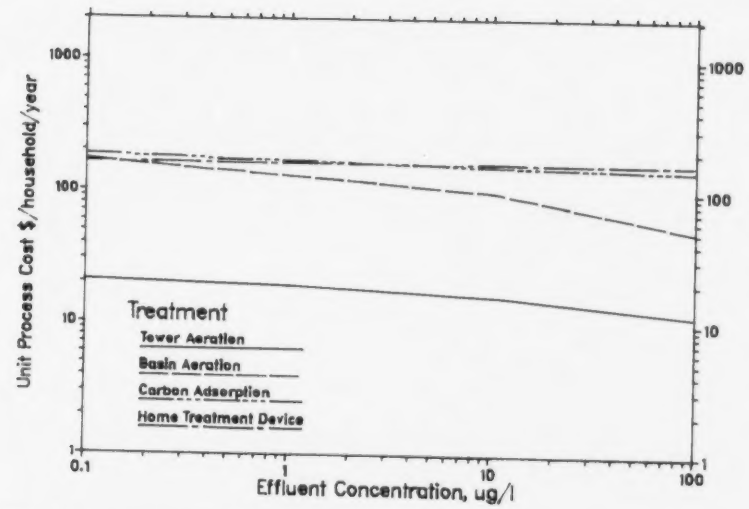

FIG. 9.—Treatment (Trichloroethylene 0.1 mgd; Influent Concentration = 1,000 µg/L; Sept. '82 Dollars)

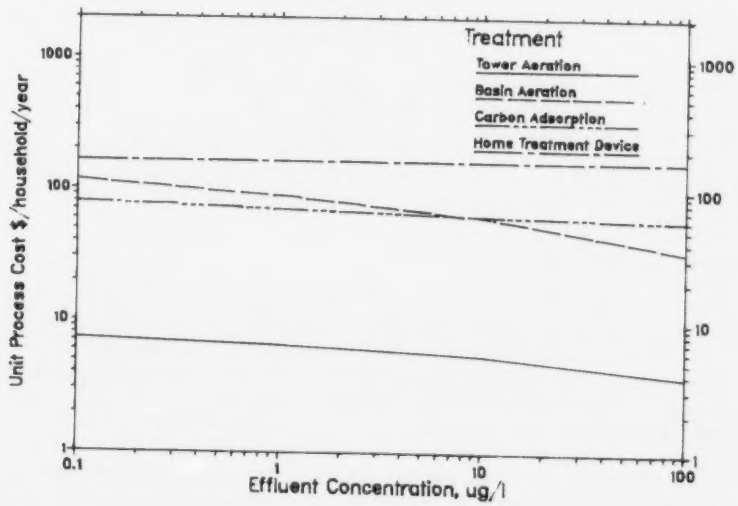

FIG. 10.—Treatment (Trichloroethylene 0.5 mgd; Influent Concentration = 1,000 µg/L; Sept. '82 Dollars)

In this section costs are based on a direct comparison of technology as opposed to the treatment train costs calculated in the previous section. The costs are also based on dollars per family per year basis.

The flow for the home units is as shown in Table 7, but the flows for

TABLE 8.—Cost Data Summary (Cost Saving Options)

Contaminant (1)	Capacity, in million gallons per day (m^3/day) (2)	Initial concentration, in micrograms per liter (3)	Percent removal (4)	Dollars per Family per Year			
				Tower (5)	Basin (6)	Carbon (7)	HUA[a] (8)
Trichloroethylene	0.1 (387.5)	100	90	11.3	50.0	145.1	160.0
		10	99	15.8	96.8	153.1	160.0
		1	99.9	18.6	128.7	167.5	160.0
		0.1	99.99	20.8	166.5	183.3	160.0
Trichloroethylene	0.5 (1,893)	100	90	3.8	33.7	58.4	160.0
		10	99	5.4	60.9	62.3	160.0
		1	99.9	6.4	87.1	69.3	160.0
		0.1	99.99	7.1	113.1	77.9	160.0

[a]Home unit adsorption.

the other technologies are based on an assumed flow of 300 gal/family/day (11.4 m^3/day), a design life of 10 yr and a unit volume of 0.25 ft^3 (0.007 m^3).

Figs. 9 and 10 show the costs associated with home treatment (replacement at one per year); basin aeration; carbon adsorption (assumed at midpoint of envelope of no reactivation and on-site reactivation curves); and tower aeration for removing trichloroethylene. Costs are calculated at the 0.1 (387.5 m^3/day) and 0.5 mgd (1,893 m^3/day) level for 90–99.99% removal.

As with the previous analysis, aeration is consistently the least costly technology. However, at 0.1 mgd (387.5 m^3/day), the home unit devices become competitive with the carbon regionalization option. Therefore, for high molecular compounds which may not be amenable to air stripping, individual home adsorption units may be cost-effective. Table 8 summarizes these costs at 90%, 99%, 99.9% and 99.99% removal.

Summary and Conclusions

It is obvious from the previous analysis that, when feasible, tower aeration is by far the most cost-effective technology for removing VOCs from drinking water. It is also the least expensive technology over a wide range of removal percentages. However, there may be cases where aeration is not cost-effective. For example, when removing "high" weight molecular compounds, adsorption is the probable technology of choice. Aeration also has some secondary effects not considered here, such as the possible need for "off-gas" control and the increased potential for the effluent stream to be corrosive in the distribution system. For low percentage removal levels at small capacity, adsorption appears to be more cost-effective than either basin or tower aeration. At the smallest sizes, home units may provide a cheaper adsorption system than central treatment. Field research in the future will concentrate on developing elements of the performance matrix for the options of aeration and adsorption, and to verify costs through case studies and determine where these technologies should be applied.

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